

# Nature and Demise of the Proto-South China Sea

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## Abstract:

The term Proto-South China Sea has been used in a number of different ways. It was originally introduced to describe oceanic crust that formerly occupied the region north of Borneo where the modern South China Sea is situated. This oceanic crust was inferred to have been Mesozoic, and to have been eliminated by subduction beneath Borneo. Subduction was interpreted to have begun in Early Cenozoic and terminated in the Miocene. Subsequently the term was also used for inferred oceanic crust, now disappeared, of quite different age, notably that interpreted to have been subducted during the Late Cretaceous below Sarawak. More recently, some authors have considered that southeast-directed subduction continued until much later in the Neogene than originally proposed, based on the supposition that the NW Borneo Trough and Palawan Trough are, or were recently, sites of subduction. Others have challenged the existence of the Proto-South China Sea completely, or suggested it was much smaller than envisaged when the term was introduced.

We review the different usage of the term and the evidence for subduction, particularly under Sabah. We suggest that the term Proto-South China Sea should be used only for the slab subducted beneath Sabah and Cagayan between the Eocene and Early Miocene. Oceanic crust subducted during earlier episodes of subduction in other areas should be named differently and we use the term Paleo-Pacific Ocean for lithosphere subducted under Borneo in the Cretaceous. There is good evidence for subduction between the Eocene and Early Miocene below Sabah, and the western limit of Proto-South China Sea subduction was the West Baram Line. The subducted slab can be imaged in the lower mantle using P-wave tomography. There was no subduction beneath Sarawak, SW of the West Baram Line, between the Eocene and Early Miocene where there was terrestrial to marginal marine deposition. The present-day NW Borneo Trough and Palawan Trough are not subduction trenches and these relatively shallow features have different origins. The NW Borneo Trough is largely a flexural response to gravity-driven deformation of the Neogene sediment wedge NW of Sabah whereas the Palawan Trough is the continent-ocean transition at the SE edge of the modern South China Sea.

## Keywords:

Subduction, Borneo, Sabah, Sarawak, Tomography

## INTRODUCTION

The late 1960s and early 1970s saw a major change in global tectonic concepts as plate tectonics became the established paradigm. For northern Borneo this was encapsulated by the abandonment of the terminology of undations and geosynclines (e.g. van Bemmelen, 1949; Haile, 1968) and the recognition that subduction had played an important part in the evolution of the region (e.g. Hamilton, 1973; Haile, 1973). However, the links between subduction and the surrounding ocean basins of the South China, Sulu and Celebes Seas (Figure 1) were controversial (see for example, Karig, 1971; Hamilton, 1973; Ben-Avraham and Uyeda, 1973). A clearer picture of Borneo tectonics was slow to emerge because key pieces of information were missing, for example, supposed melanges in Borneo interpreted by Hamilton (1973) were poorly dated, the age of the South China Sea was unknown and was suggested to be Cretaceous by Ben-Avraham and Uyeda (1973) in an early review of geophysical data, and consequently there were quite different ideas concerning the age, location and polarity of subduction zones recorded in Borneo geology.

For the South China Sea this situation had changed by 1980 when Taylor and Hayes identified spreading to have been active from the mid-Oligocene to Early Miocene based on marine geophysical data, principally new magnetic anomaly data, which they followed by reconstructions of the region (Taylor and Hayes, 1983). Their interpretation has subsequently been modified, but largely supported, by later studies (e.g. Briais et al., 1993; Barckhausen and Roeser, 2004; Barckhausen et al., 2014). Ocean drilling (Li et al., 2014, 2015) has subsequently confirmed the age of the oceanic crust of the South China Sea, although the exact ages of the beginning and ending of spreading remain controversial (compare Barckhausen et al., 2014, 2015 with Chang et al., 2015).

### Proto-South China Sea

The term Proto-South China Sea (Figure 2) was first used by Hinz et al. (1991) for a large oceanic embayment (Figure 2C) situated in the latest Cretaceous between Indochina and South China in the north and Borneo in the south, that pre-dated the formation of the present-day South China Sea. The oceanic crust of this basin was suggested by Hinz et al. (1991) to have been eliminated by subduction beneath a Borneo microcontinental plate by the Middle Miocene and as subduction proceeded, extension of the continental margin to the north of the Proto-South China Sea led to formation of the modern South China Sea. It is clear that the concept of the Proto-South China Sea in Hinz et al. (1991) was derived from earlier studies. Taylor and Hayes (1980) inferred that a basin older than the South China Sea had existed south of Reed Bank before it was eliminated by subduction beneath Borneo and Taylor and Hayes (1983) showed this as Mesozoic oceanic crust on their Paleocene reconstruction (Figure 2B). Hinz et al. (1991) presented a latest Cretaceous reconstruction

(Figure 2C), which is almost identical to the Taylor and Hayes (1983) Paleocene reconstruction (Figure 2B). Holloway (1981, 1982) presented a very similar reconstruction for the Late Cretaceous and Paleocene (Figure 2A).

### **Paleo-South China Sea**

Gatinsky and Hutchison (1986) used the term Paleo-South China Sea for ocean crust north of Borneo in the Jurassic–Cretaceous (150–120 Ma) representing the western part of a Paleo-Pacific ocean. They interpreted it to have been subducted beneath Borneo in the Paleogene (60–40 Ma) as the South China Sea opened, based on Taylor and Hayes (1983). Although the ages adopted were about 20 million years older than interpreted by Taylor and Hayes (1983) this Paleo-South China Sea was a Mesozoic ocean subducted beneath Borneo in the Cenozoic, as confirmed by Hutchison (1989), and therefore similar to the Proto-South China Sea of Hinz et al. (1991). Subsequently, the term Paleo-South China Sea has been almost completely abandoned. For example, in later studies Hutchison (1996) used Proto-South China Sea instead. Clift et al. (2008) used it for lithosphere subducted beneath Borneo between the Eocene and Early Miocene which all other authors call the Proto-South China Sea.

### **Features of the Proto-South China Sea**

Since the term Proto-South China Sea was introduced by Hinz et al. (1991) it has been used in a broadly similar way by many authors (e.g. Rangin et al., 1990a, 1990b; Rangin and Silver, 1991; Lee and Lawver, 1994, 1995; Tongkul, 1994; Hall, 1996, 2002; Cullen, 2010, 2014), although there have been differences of opinion concerning the size of the ocean basin. Key features of this conceptual Proto-South China Sea are that it formerly occupied the area south of Indochina and South China where the modern South China Sea is situated, its oceanic crust had a Mesozoic age, and it has been completely eliminated by subduction. Subduction began in the Eocene on the southern side of the Proto-South China Sea and ceased in the Early Miocene and the oceanic lithosphere was subducted beneath northern Borneo (Holloway, 1981, 1982; Taylor and Hayes, 1983; Hinz et al., 1991), the Cagayan arc (Hinz et al., 1991) and possibly parts of the Philippines (Holloway, 1981, 1982). The subduction zone was shown as extending as far west as offshore Sarawak. The Proto-South China Sea narrowed towards the west and its western end met the Sunda Shelf in a zone of dextral strike-slip faulting. The southward subduction was terminated by collision between continental crust of South China origin and a volcanic arc from Sabah to the Cagayan Ridge. All the models (Holloway, 1981, 1982; Taylor and Hayes, 1983; Hinz et al., 1991) showed large counter-clockwise rotation of Borneo during subduction.

However, subsequently the term has also been used for inferred oceanic crust, now disappeared, of quite different age. Some authors have considered that southeast-directed subduction continued until much later than originally proposed, usually based on the misconception that the NW Borneo Trough and Palawan Trough are, or were recently, sites of subduction, a suggestion first made by Hamilton (1973). Hamilton (1979) identified the present-day offshore linear NE-striking troughs as inactive, but relatively young, subduction trenches. He suggested that what he called the NW Borneo Trench, where he interpreted subducted oceanic crust to be visible on seismic reflection profiles, would be interpreted as active were it not for the absence of seismicity, and explicitly labelled his Palawan Trench as “inactivated in Late Miocene”. This continues to cause confusion (see Hutchison, 2010b) and has led some authors to consider that subduction beneath northern Borneo continues to the present day (e.g. Tongkul, 1991; Rangin et al., 1999a; Simons et al., 2007). Finally, some authors have challenged the existence of the Proto-South China Sea altogether, notably those who have advocated South China Sea formation to be a consequence of India indentation of Asia (e.g. Tapponnier et al., 1986; Replumaz and Tapponnier, 2003; Replumaz et al., 2004).

In this paper we explain how the term Proto-South China Sea has been used for oceanic lithosphere subducted at different times under Borneo. We highlight differences in the geological history of different parts of northern Borneo with the aid of a simplified geological map (Figure 3) and stratigraphic chart (Figure 4) for the Late Cretaceous to Quaternary and show how the geology of northern Borneo is linked to different episodes of subduction. We then discuss the evidence for Proto-South China Sea subduction between the Eocene and Early Miocene, and show that the subducted lithosphere can be identified in the mantle below Borneo and the Philippines.

## **CRETACEOUS TO EOCENE**

### **Stratigraphy**

Sarawak has been divided into a number of sub-parallel zones (Figure 5) with different stratigraphic character, which from south to north are the West Borneo Basement (which broadly equates to the Schwaner Mountains of Kalimantan), Kuching Zone, Sibuan Zone and Miri Zone (Haile, 1974). The Kuching Zone is composed of fluvial to marginal marine sediments (Figure 4). These include the Kayan Sandstone and Silantek Formation, Tutoop Sandstone (Plateau Sandstone) and Ketungau Formation of the Ketungau Basin in West Sarawak and NW Kalimantan (Haile, 1957; Liechti et al., 1960; Wolfenden and Haile, 1963; Wilford and Kho, 1965; Muller, 1968; Kanno, 1978; Tan, 1979; Heryanto and Jones, 1996) deposited from the Late Cretaceous (Maastrichtian) to the Middle Eocene (Liechti et al., 1960; Tan, 1979; Pieters et al., 1987; Morley, 1998; Breitfeld, 2015).



The boundary between the Kuching Zone and Sibu Zone is the Lupar Line (Haile, 1974). The Sibu Zone (Figure 4) includes sedimentary rocks of similar age to the Kuching Zone, but in contrast is predominantly composed of turbiditic deep marine sediments of the Belaga Formation (Kirk, 1957; Haile, 1957; Liechti et al., 1960; Wolfenden, 1960; Tan, 1979; Hutchison, 1996; Bakar et al., 2007; Galin, 2013), which together with the Lupar Formation (and the Embaluh Formation in Kalimantan) form the Rajang Group (Haile, 1962; Tate, 1991; Hutchison, 1996; Moss, 1998). The metamorphosed turbiditic Mulu Formation of the Miri Zone (Liechti et al., 1960; Haile, 1962) and the metamorphosed turbiditic Sapulut Formation in Sabah (Collenette, 1965) are lateral equivalents and can therefore be grouped within the Rajang Group. In NE Kalimantan the turbiditic deep marine to slope Mentarang and Lurah Formations are potential equivalents of the Rajang Group, while the Long Bawan Formation may include marine successions (BRGM, 1982). However, the three NE Kalimantan formations are not very well studied, and their correlation with Sarawak and Sabah is only poorly understood.

Recent work on heavy mineral and detrital zircon geochronology shows that the Rajang Group is the lateral deep marine equivalent of the fluvial to shallow marine deposits in the Kuching Zone (Galin, 2013; Breitfeld, 2015) and these formed part of a single continental margin sedimentary system.

### **Rajang Group: Accretionary prism?**

The deep water and deformed character of much of the Rajang Group led to the suggestion that it represented an accretionary prism (e.g. Tan, 1979, 1982) related to southward subduction at the Lupar Line, which was therefore a former subduction zone. Haile (1973) discussed the Lupar valley and concluded it had some features of a former subduction zone, but many that were missing. He also commented that the Rajang Group contains no chert or ophiolites and is not a melange. Hutchison (1996) interpreted the Rajang Group as a north-facing accretionary prism, related to Late Cretaceous (85 Ma) to Late Eocene (45 Ma) southwards subduction beneath the Kuching Zone, i.e. at the Lupar Line (Figure 6). Hutchison (2010a) included the Belaga Formation of Sarawak, the Embaluh Group, Malinau Formation and Mentarang Formation of Kalimantan and the Sapulut and Trusmadi Formations of Sabah. Hutchison (1996, 2005, 2010a) argued that older parts of the Rajang Group were accretionary, but that subduction ceased in the Paleocene before most of the turbidites were deposited. For the younger turbidites he followed Moss (1998) who suggested they were deposited in a remnant ocean basin. Moss (1998) specifically excluded an accretionary setting and argued that subduction had ceased in the Late Cretaceous based on an absence of southwards dipping thrusts and, southward rather than northward, younging of the Embaluh Group, which unlike much of the other formations in the Rajang Group is not metamorphosed. Williams et al. (1988) and Moss (1998) concluded that

subduction-related magmatism in the Schwaner Mountains arc had ceased by about 80 Ma, and Hutchison (1996) observed that the subduction history inferred by Tan and Lamy (1990) and Hazebroek and Tan (1993), from Late Cretaceous to Late Eocene, is not marked by subduction-related Eocene volcanic arcs.

## **Oceanic subduction**

According to Hutchison (1996) the Rajang Group was a north-facing accretionary prism (Figure 6), related to Cretaceous to Eocene southwards subduction of the Danau Sea of Haile (1994). He insisted that the Danau Sea was not related to the younger South China Sea and should not be referred to as the Proto-South China Sea. Despite this, he nonetheless showed subduction of a Proto-South China Sea in the Late Cretaceous beneath the Rajang Group (Figure 6). Hutchison (2010a) also shows the Proto-South China Sea subducting southwards under Sarawak in the Early to Late Cretaceous (130-80 Ma), and Hutchison stated that the Sibu Zone was deposited on Proto-South China Sea oceanic crust. Although no maps were provided Hutchison (2010a) reported that “the northern and southern Sundaland continents continued to converge until collision eliminated the Proto-South China Sea ocean basin, with small remnants uplifted as ophiolite along the Lupar Line. Extinction of the turbidite basin and uplift of the compressed Sibu Zone was interpreted by Hutchison (2005) to have taken place at the end of the Eocene, during the Sarawak Orogeny, discussed further below.

Moss (1998) continued with this usage when he commented on earlier interpretations of ocean crust subducted under Borneo during the Late Cretaceous as “invariably ascribed to subduction of a large proto-South China Sea, with the Schwaner Mountain granites marking the position of the former volcanic arc”. In contrast to Hutchison (1996), Moss argued that oceanic subduction beneath Borneo had ceased by about 80 Ma and the Rajang-Embaluh turbidites were deposits of a remnant oceanic basin (Figure 7) and were not an accretionary complex directly related to subduction. King et al. (2010) appear to be the only other authors who have named crust subducted during the Cretaceous under Borneo as a Proto-South China Sea.

It is clear that both Hutchison (1996), Moss (1998) and later King et al. (2010) used the term Proto-South China Sea in an entirely different way from previous authors. This oceanic crust was subducted beneath Sarawak and NW Kalimantan, but subduction had ceased either during the Cretaceous or by the Late Eocene and was completed long before subduction of oceanic crust began beneath Sabah and Cagayan as proposed by Hinz et al. (1991). We consider it is confusing to call both the Proto-South China Sea. It is also arguable if pre-Cenozoic subduction should be related to the South China Sea in any way; many authors consider Cretaceous subduction under Borneo as part of a Paleo-Pacific subduction margin. We therefore suggest restricting the name Proto-South China Sea

and acronym (PSCS) to the slab subducted mainly beneath Sabah and Cagayan between the Eocene and Early Miocene. We call the lithosphere subducted under Borneo in the Cretaceous the Paleo-Pacific Ocean (PPO).

Our view is that the various melanges including ophiolitic rocks (Lubok Antu, Boyan, etc.) are all part of a wide accretionary zone at the eastern margin of Asia and Sundaland which includes fragments of continental crust (e.g. the Semitau block of Metcalfe, 1990; rocks dredged from the Dangerous Grounds reported by Kudrass et al., 1986) that formed during Triassic to Cretaceous subduction of the Paleo-Pacific Ocean. Hall and Sevastjanova (2012) suggested that the Lupar Line is not a collisional suture, but a strike-slip zone separating the emergent area of the Schwaner Mountains, coastal plains and shallow shelf to the south, from a deep-water turbidite basin further north. We consider that displacements on this strike-slip zone exhumed some of the ophiolitic rocks in the Lubok Antu melange, probably between the Late Cretaceous and Eocene.

## **EOCENE TO MIOCENE**

### **Stratigraphy**

The regions in which the Cretaceous and Paleogene subduction episodes occurred are separated by the West Baram Line (Figure 3) which is the position of a major stratigraphic change in the Middle to Late Eocene (Figure 4). To the SW of the West Baram Line deep water sedimentation ceased and the Rajang Group is overlain by terrestrial to shallow marine sediments of the Miri Zone, which are largely undeformed. Hutchison (e.g. 1996, 2005) attributed this change to a collisional event named by him the Sarawak Orogeny.

### **Sarawak Orogeny**

Hutchison (1996) proposed the Sarawak Orogeny deformed the deep water sediments of the Rajang Group in the Late Eocene at c.45 Ma due to collision of a Balingian–Luconia continental block with SW Borneo about 15 Ma earlier, following southwards subduction which terminated by c.60 Ma. The age of the orogeny was based on unconformities described by earlier workers (Wolfenden, 1960; Adams and Haak, 1962; Haile and Ho, 1991). Later, Hutchison (2004, 2005) assigned the orogeny a younger age of c.37 Ma and described it as the result of indentation of a promontory of northern Sundaland following closure of the proto-South China Sea (Hutchison, 2010a). Hall (2012) and Hall and Sevastjanova (2012) have questioned the age and interpretation of the unconformity.

Borneo Geological Survey geologists did recognise an episode of folding in the Late Eocene (Kirk, 1957; Wolfenden, 1960; Haile, 1962), but before 37 Ma, and as one event in a long Cretaceous

to Eocene history of deformation. Wolfenden (1960) identified an unconformity older than uppermost Eocene, and Adams and Haak (1962) showed it was older than the East Indies Letter Stage Tb, indicating that the oldest rocks above the unconformity include the oldest part of the Upper Eocene, which would mean the unconformity is older than c. 40 Ma. Haile and Ho (1991) did not date it. In Sarawak, Wolfenden (1960) noted the absence of a marked angular unconformity in some areas and commented that the “stratigraphic evidence is difficult to reconcile with the concept of an upper Eocene orogeny that caused the entire... ..Rajang Group to be folded” and observed that “deformation accompanied deposition”.

Syn-depositional deformation in the deep-water basin occurred between the Late Cretaceous and the Late Eocene. The Sarawak Orogeny was suggested by Hall and Sevastjanova (2012) to mark not a collisional event, but a regional plate boundary reorganisation that occurred when Australia began to move north at about 45 Ma, initiating subduction on the north side of Borneo (Hall et al., 2008), beneath Sabah and Cagayan, and south of Java (e.g. Hall et al., 2009; Hall, 2002, 2012). The unconformity which terminated the deposition of the Rajang Group and its equivalents in the Middle to Late Eocene is named here the ‘Rajang Unconformity’ (Figure 3).

### **Late Eocene change: Sarawak to Sabah**

Whatever the cause, there was an important change in Sarawak in the Late Eocene and highly deformed deep water turbidites are unconformably overlain by slightly tilted, but otherwise undeformed, terrestrial/marginal marine sedimentary rocks (Figure 4). In Sarawak, sedimentation resumed in the Late Eocene to Early Oligocene in the Miri Zone and potentially in the Sibu Zone with the fluvial to marginal marine Tatau and Nyalau Formations of Late Eocene/Early Oligocene to Early Miocene age (Kirk, 1957; Wolfenden, 1960; Hassan, 2004; Wong, 2011) SW of the West Baram Line.

NE of the West Baram Line, sedimentation was dominated by deep marine successions. The Setap Shale is the deep marine time equivalent of the Nyalau Formation in the Miri Zone (Haile, 1962; Hutchison, 2005), and the Temburong and Crocker Formations in Brunei and Sabah represent shaly to sand-dominated turbidites (Collenette, 1958, 1965; Wilson and Wong, 1964; van Hattum et al., 2006, 2013). The turbiditic Labang Formation (Collenette, 1965; Haile and Wong, 1965) and the marine Kulapis Formation (Newton-Smith, 1967; Clennell, 1992; Noad, 1998) are the eastern equivalents of the Crocker Formation. An exception to the overall deep marine character is the Upper Eocene to Lower Miocene Melinau Limestone Formation, which is interpreted as a local marine carbonate platform some distance from the shore (Liechti et al., 1960; Adams and Haak, 1962; Adams, 1965). However, Adams and Wilford (1972) described other Oligocene limestone exposures in the Melinau region which they interpreted as deep water limestones.

In Sabah the partially metamorphic Eocene Trusmadi Formation (Collenette, 1958, 1965) could represent the older parts of the Crocker Formation (as shown in Figure 4), but could also be part of the Rajang Group below the unconformity as shown by Hutchison (2005). The Crocker Formation is terminated by the Early Miocene Top Crocker Unconformity (TCU) that separates it from younger fluvial to shallow marine sediments (van Hattum, 2005; Hall et al., 2008; van Hattum et al., 2013).

### **Sarawak: western limit of Proto-South China Sea subduction**

All the early interpretations of subduction under Borneo (Holloway, 1981, 1982; Taylor and Hayes, 1983; Hinz et al., 1991) interpreted subduction to have begun beneath Borneo in the Eocene in an area which extended far to the west, into or beyond Sarawak (Figure 2). It is now evident that the westernmost limit of Proto-South China Sea subduction was the West Baram Line. Recent work also now makes clear that grouping together the deep water Rajang Group and deep water Crocker Formation (and associated formations) is unjustified and misleading. During the period when the Crocker Formation was being deposited NE of the West Baram Line there was terrestrial to shelf sedimentation to the SW (Figures 3 and 4).

Although the idea of south-directed subduction was introduced quite early in the 1970s (Hamilton, 1973, 1979; Holloway, 1981, 1982; Taylor and Hayes, 1983; Hinz et al., 1991) and incorporated in many later tectonic interpretations of Sabah and Sulu Sea (e.g. Hutchison, 1989; Hazebroek and Tan, 1993; Hall, 1996; Hutchison et al., 2000; Hall and Wilson, 2000) it is worth revisiting the evidence for subduction since both the size and even the existence of the Proto-South China Sea have been challenged in recent years.

### **Evidence for subduction c. 45-20 Ma**

The case for subduction was strongly influenced by Hamilton's early interpretations, particularly his suggestions of subduction melanges. He drew attention to an association of melanges and broken formations, calc-alkaline igneous rocks, cherts, basalts, ophiolite fragments, and serpentinised peridotites and interpreted them as the result of Early and Middle Cenozoic subduction beneath northern Borneo.

### **Basement**

Northern Borneo has a basement of ophiolitic rocks, but with possible older crust indicated by K-Ar ages of igneous and metamorphic rocks. The Chert-Spilitic Formation includes cherts and limestones of Cretaceous age. Metamorphic rocks were described as crystalline basement (Reinhard

and Wenk, 1951; Dhonau and Hutchison, 1966; Koopmans, 1967) and most of the protoliths are basic and all could be deformed ophiolitic rocks. Omang and Barber (1996) suggested the crystalline basement rocks are essentially equivalent to the Cretaceous Darvel Bay ophiolite complex (Dhonau and Hutchison, 1966; Hutchison, 1975, 1978). They are intruded by dioritic and granitic rocks which could represent arc plutonic rocks intruded into an older ophiolitic basement. Hall and Wilson (2000) concluded that descriptions by Leong (1974) and earlier workers suggest formation of the crystalline basement in a Mesozoic intra-oceanic arc. There are however, a few rocks described which are of possible continental origin, such as andalusite-garnet-mica and sillimanite-garnet schists (Leong, 1974), although none of these rocks are dated. Fragments of ophiolitic rocks are found as clasts in Eocene sediments, suggesting that the Sabah ophiolite complex had been obducted in either the latest Cretaceous or earliest Paleogene (Omang and Barber, 1996). No Cenozoic ocean floor basalts or deep marine sediments that could represent Paleogene accreted oceanic crust are known.

### HP-LT metamorphic rocks

High pressure metamorphic rocks, including HP-LT rocks typical of subduction metamorphism, have been reported from a number of parts of Sabah. None are dated. Eclogites were described from the Dent peninsula area (Reinhard and Wenk, 1951) and Haile and Wong (1965) reported glaucophane-bearing rocks as well as a variety of other metamorphic rocks. Morgan (1974) estimated pressures and temperatures of 850°C and 19 kbar for the garnet pyroxenites from the Dent peninsula indicating upper mantle conditions. Parkinson et al. (1998) suggested these rocks, accompanied by garnet-kyanite amphibolite, eclogite and blueschist, found within Miocene conglomerates, had a subduction origin.

Kirk (1968) mentioned quartz-muscovite-glaucophane schist and glaucophane amphibolites as float in the Labuk River north of Telupid. Johnston and Walls (1974) reported glaucophane-bearing metabasalts from the Telupid area which could be part of the Chert–Spilite Formation or Crocker Formation. Hutchison et al. (2000) mentioned piemontite and confirmed glaucophane-epidote facies rocks from Telupid. Leong (1978) suggested all these rocks belonged to a Sabah subduction-related blueschist belt.

### Crocker and associated formations

Hamilton (1973, 1979) described and illustrated numerous examples of deformed deep-water Eocene and Oligocene clastic sediments of the Crocker Formation which he interpreted as part of a subduction-imbricated terrain. Subsequent studies have confirmed the deep water turbidite character of the sediments (e.g. Crevello, 2002; van Hattum, 2005; Lambiase et al., 2008; Cullen et al., 2012; van

Hattum et al., 2013) and the common syn-sedimentary deformation. The character of all the deep-water sediments and the syn-depositional deformation of the Crocker Formation and associated formations such as the Temburong, Kulapis and Labang Formations is consistent with an accretionary forearc setting, with elevated forearc highs from which ophiolitic debris was eroded (van Hattum, 2005; van Hattum et al., 2006, 2013) and where limestones (e.g. Gomantong Formation) may have been deposited (McMonagle et al., 2011). However, none of these features requires a subduction-related forearc setting. Rangin et al. (1990a) described the chaotic complexes of southern Sabah as large SE-dipping thrust slices imbricated with a Late Paleogene to Early Neogene volcanic arc sequence, and with large thrust slices of dismembered ophiolites which does suggest an accretionary forearc setting.

The heavy mineral assemblages of the Eocene-Lower Miocene Crocker Formation are dominated by the ultra-stable minerals zircon, tourmaline and less abundant rutile, with variable quantities of other minerals which are locally abundant including garnet and apatite (van Hattum, 2005). Chrome spinel is nearly always present, but never exceeds 4% of the total heavy mineral suite. Pyroxene and amphibole are present in a few samples which could indicate a volcanic arc source. No detrital HP-LT minerals have been found so far in the Crocker Formation (van Hattum, 2005). Euhedral unabraded zircons are quite common. However, the youngest zircon in the 4 samples from which detrital zircons have been dated is 73 Ma (van Hattum et al., 2006, 2013) and is therefore much older than the depositional age. The heavy mineral assemblages of the Eocene Trusmadi Formation sandstones resemble those of the Crocker Formation and in the single sample from which detrital zircons have been dated the youngest zircon is 50 Ma indicating Eocene igneous activity. The Oligocene Labang Formation contains some of the least mature sandstones of Sabah, with a possible magmatic arc provenance based on their light and heavy mineral compositions (van Hattum, 2005). Labang Formation sandstones contain abundant volcanic lithic grains. Typical heavy minerals include zircon, tourmaline, apatite, garnet, rutile, chrome spinel, pyroxene and hornblende. The preservation and relative abundance of pyroxene and hornblende suggest a volcanic arc contribution. No detrital zircons from the Labang Formation have yet been dated.

## Volcanic rocks

Pre-Neogene volcanic rocks are rather uncommon in west and central Sabah. Basalts are sometimes found intercalated in the Crocker Formation, presumably faulted, although we have not seen contacts, and could represent contemporaneous igneous activity, but could alternatively be tectonically incorporated slices of basement.

An obvious Paleogene volcanic arc is not known. However, the likely position of the arc suggests it could be buried beneath Neogene basins of central and eastern Sabah. Near Sandakan (Figure 1), at such a position, Rangin et al. (1990a) reported the mosque is built on a folded sequence of tuffs, greywackes and massive andesitic flows and microbreccias. Late Oligocene nannoplankton (NP25) were found in this sequence, which is covered unconformably by slightly deformed clastic sediments of the Neogene Sandakan Formation. Bergman et al. (2000) reported a K-Ar age of  $77 \pm 4$  Ma from plagioclase (they commented this may be anomalous due to very low K content and possible excess  $^{40}\text{Ar}$ ) and an apatite fission track age of  $34 \pm 8$  Ma from an andesite tuff in this sequence.

Detrital zircons in Paleogene sandstones (van Hattum et al., 2006, 2013) indicate a maximum depositional age (MDA) of 56 Ma for the Sapulut Formation and 50 Ma for the Trusmadi Formation, confirming Eocene volcanic activity. No younger ages have been obtained from detrital zircons in the Crocker Formation, although only 4 sandstone samples have been dated. Probable tuff bands are present in the Crocker Formation in Sabah, but none of these volcanic horizons have yet been dated.

Suggate (2011) dated detrital zircons from 11 samples of Neogene sandstones deposited above the TCU of which 7 contain Eocene zircons (41-48 Ma). These could have come from Borneo, but some in the Kudat Formation could come from Palawan (Suggate and Hall, 2013; Suggate et al., 2014). However, one Miocene Tanjong Formation sample from one of the circular basins in Sabah contains a population of Eocene to Early Miocene zircons with ages of 48-22 Ma (Suggate, 2011) which can only have come from a Borneo source indicating Paleogene volcanic activity.

## Cagayan Ridge

Hamilton (1979) tentatively suggested the Cagayan Ridge (Figure 1) could be a Paleogene Arc. Hinz et al. (1991) reported that petrological and geochemical data indicates continental crust below Oligocene to Miocene volcanic rocks. Kudrass et al. (1990) dredged samples of andesites and dacites from the northernmost Cagayan Ridge. They reported K-Ar ages of 158-36 Ma from amphiboles which may be inherited xenocrysts, and the oldest plagioclases of 26-22 Ma. However, they also mentioned problems of excess Ar and Ar loss and concluded there was definite Neogene and possibly some older volcanic activity. Rangin and Silver (1991) reviewed all the data from the Cagayan Ridge after ODP Leg 124 drilling. They observed that the oldest rocks dredged at the northern end of the ridge were close to the axis of a major canyon flowing SE from Panay Island, where the pre-Neogene volcanic rocks of the Philippine arc are exposed. Thus, they were confident of Neogene volcanic activity at 14.7 Ma at Sites 769 and 771 (Figure 1), but were cautious about older volcanism, although they suggested the Cagayan Ridge may have extended SW as far as the Oligocene volcanoclastic rocks of the Sandakan area in Sabah.



## **Discussion**

Overall, the case for Paleogene subduction beneath northern Borneo is strong, but not indisputable. The evidence suggests a pre-Cenozoic ophiolitic/arc basement in Sabah, with hints of deep continental crust (Leong, 1974; Macpherson et al., 2010). There is convincing evidence of HP-LT subduction-related metamorphism, but the age is not known and could be Mesozoic. The Crocker and associated formations are typical of a volcanic forearc margin, but many of the features could be explained by a Paleogene deep-water continental margin setting without subduction. Most of the sediment came from the unroofed Cretaceous Schwaner magmatic arc, either directly or indirectly, and the Tin Belt of the Thai-Malay peninsula (van Hattum et al., 2006, 2013). There is good evidence for Paleogene volcanism from outcrops near Sandakan, volcanic lithic grains in the Labang Formation, heavy minerals in some sandstones, and ages of detrital zircons in Neogene sediments. However, given the limited number of samples that have been dated it is clear that more work is required to determine the age and importance of volcanic activity. Given the interpreted size of the Proto-South China Sea (Holloway, 1981, 1982; Taylor and Hayes, 1983; Hinz et al., 1991) more evidence of a Paleogene arc might be expected, although the subducted embayment narrowed westwards, which would have reduced the amount of subduction, and an arc could be buried below Neogene sediments. Subduction does not always produce magmatic products (e.g. Macpherson and Hall, 2002) and there are several active subduction zones in the region (North Sulawesi Trench, Philippine Trench) without associated volcanic arcs. Alternatively, modifications to reconstructions could reduce the interpreted size of the Proto-South China Sea (Cullen, 2010).

## **SEISMIC TOMOGRAPHY**

It is now accepted that the mantle contains a record of subduction, because subducted lithosphere produces a strong temperature anomaly which causes slabs to be observed as regions with relatively high seismic velocities. One important test of tectonic models involving subduction is to examine the structure of the mantle, since high-resolution P-wave seismic tomography can reveal such velocity anomalies. Is the Proto-South China Sea identifiable?

### **Where is the Proto-South China Sea?**

Rangin et al. (1999b) were the first to consider mantle structure and presented three options based on different tectonic models for the Proto-South China Sea (PSCS): large (Holloway, 1981, 1982; Taylor and Hayes, 1983; Hinz et al., 1991), none (Tapponnier et al., 1986), or small (Rangin et

al., 1999b). They pointed out that no large anomaly existed in the position they expected for the PSCS below northern Borneo and the Sulu Sea. This could mean the PSCS had not existed or a high velocity anomaly was not obvious because the PSCS had been small. Alternatively, they proposed that the PSCS was north of its expected position because of clockwise rotation of Borneo, speculated to have been initiated 10 to 15 million years ago and inferred from GPS measurements (Rangin et al., 1999a) made between 1994 and 1996. They concluded that the PSCS could be identified as a high velocity anomaly present beneath the present South China Sea at depths between 400 and 660 km.

Tang and Zheng (2013) interpreted regional surface wave tomography to show a Proto-South China Sea slab of 500 km length in the upper mantle beneath northern Borneo which is longer than estimated by Rangin et al. (1999b), but smaller than interpreted by the Hall (1996, 2002, 2012) reconstructions.

Cullen (2010) also questioned the evidence for a PSCS slab. He reported that P-wave tomographic images of Hafkenscheid (2004) show a high velocity anomaly between 200 km and 300 km under northern Borneo, but concluded it was difficult to relate this to subduction under NW Borneo. He also observed that tomographic images in Replumaz et al. (2004) do not show this anomaly and concluded that although these do not preclude the presence of a subducted slab beneath NW Borneo (since other supposed subduction zones are not imaged) they indicate a relatively small Proto-South China Sea. However, because of its relatively aseismic character the northern Borneo region has poor resolution using P-wave tomography. This could account for the differences between the Hafkenscheid (2004) and Replumaz et al. (2004) images, both of which are based on Utrecht P-wave tomographic models of Spakman. Resolution tests (Hall and Spakman, 2015) show the high velocity anomaly between 200 km and 300 km could be an artefact.

But the lack of resolution in P-wave tomographic models for Borneo is not the main problem. There is a more compelling reason why those searching for the PSCS in the mantle have not found it; they have been looking in the wrong place.

Hall and Spakman (2015) reviewed mantle structure beneath SE Asia using a significantly improved P-wave tomographic model compared to those of previous authors. The tomographic images record subduction beneath the SE Asian region to depths of approximately 1600 km. In the lower mantle a broad and deep anomaly imaged in earlier models below SE Asia now can be seen to have a resolvable internal structure. Upper mantle anomalies beneath SE Asia typically record subduction during the last 10 to 25 Ma (Hall and Spakman, 2015) and the PSCS was subducted before 20 Ma. Thus, if it is not an artefact, the shallow anomaly discussed by Cullen (2010) below North Borneo is young and cannot be due to subduction of the PSCS. Secondly, Borneo and the SE margin of Sundaland have rotated since the Early Miocene (Hall, 1996, 2002, 2012) and therefore the upper mantle directly beneath Borneo is not the place to look. In contrast, in the lower mantle there is an

anomaly north of the equator (Hall and Spakman, 2015) that can be traced from below central Borneo with a SW-NE strike to 15°N under the central Philippines (Figure 8A). The tomographic images show an anomaly now at depths below 700 km with a lateral extent consistent with a wide Paleogene Proto-South China Sea which narrowed and terminated towards the SW, and a position consistent with a large Neogene rotation of Borneo. Hall and Spakman (2015) suggest this anomaly is the Proto-South China Sea which subducted southwards from 45 to 20 Ma beneath Sabah and Cagayan consistent with tectonic models (Figure 8B). Figure 8B shows essentially the tectonic model originally proposed by Holloway (1981, 1982), Taylor and Hayes (1983) and Hinz et al. (1991), but with a later rotation of Borneo, based on subsequent palaeomagnetic work (reviewed by Fuller et al., 1999) as discussed by Hall et al. (2008). The other principal difference is that the early models showed subduction of the Proto-South China Sea beneath Sarawak from the Eocene to the Middle Miocene whereas we suggest there was no subduction SW of the West Baram Line beneath Sarawak during this interval (Figure 8B).

## NEOGENE

In the Early Miocene the attenuated South China continental margin collided with Sabah and Cagayan terminating subduction, an event which Hutchison (1996) named the Sabah Orogeny. Collision completely eliminated the Proto-South China Sea. SW of the West Baram Line in Sarawak there was little or no deformation. NE of the West Baram Line, the Sabah Orogeny deformed and elevated much of Sabah, and probably Palawan, and produced a major regional unconformity (Figure 4), the Top Crocker Unconformity (TCU of van Hattum et al., 2006, 2013).

The Crocker Formation in western Sabah is unconformably overlain by the Lower Miocene shallow marine Meligan Formation (Wilson and Wong, 1964) and Kudat Formation. To the east of the Crocker Mountains during the Middle and Late Miocene there was subsidence and deposition of a thick succession of fluvio-marine deposits (Noad, 1998; Balaguru et al., 2003; Balaguru and Nichols, 2004) in the Central Sabah Basin (Hutchison, 1992) whose remnants are now found in the circular basins of eastern Sabah (Tongkul, 1993; Clennell, 1996; Balaguru et al., 2003; Tongkul and Chang, 2003).

The collision caused emergence of much of Sabah and the present central highlands of northern Borneo, with folding and thrusting of both basement and cover. However, by the end of the Early Miocene much of present-day Sabah was below or close to sea level (Noad, 1998; Balaguru et al., 2003; Hall et al., 2008) with probably a low elevated range of hills at the position of the Crocker Mountains. Because there are few Neogene rocks in western Sabah this is uncertain, but in Brunei and Sarawak Neogene rocks are preserved and the shelf edge moved broadly northwestwards from the

Middle Miocene onwards (e.g. Sandal, 1996; Hazebroek and Tan, 1993; Hutchison, 2005; Cullen, 2010), suggesting a gradual rise and widening of the Crocker Mountains during the Middle and Late Miocene.

To the west of the shelf edge in offshore Brunei and Sabah, and NE of the West Baram Line, is a thick Middle Miocene to Recent deep-water clastic wedge that thins northwards. This is deformed by folds and thrusts to form a wide and active fold and thrust belt between the coast and the NW Borneo Trough (Tan and Lamy, 1990; Hazebroek and Tan, 1993; Hinz et al., 1989; McGilvery and Cook, 2003; Morley et al., 2003; Ingram et al., 2004; Franke et al., 2008, 2011; Morley and Leong, 2008; Hesse et al., 2009; Gartrell et al., 2011).

## **PRESENT**

The NW Borneo–Palawan Trough and offshore Sabah fold and thrust belt are often interpreted as features resulting from collision, regional compression or subduction. However, there is no seismicity, dipping slab or volcanicity indicating subduction, nor obvious causes of compression.

The area around northern Borneo is largely free of seismicity (Hamilton, 1979; Engdahl et al., 1998). All hypocentres close to Borneo are shallow, with depths less than 50 km, and a majority are shallower than 30 km. Earthquakes for which there are moment tensor solutions show an inconsistent pattern (Simons et al., 2007). In the SE, beneath the Celebes Sea and Mangkalihat peninsula, most solutions indicate NE-SW compression, whereas those further north, mainly beneath the northeast Sabah coast and the Sulu Sea, suggest predominantly NW-SE extension and some strike-slip movements.

GPS observations (Simons et al., 2007) indicate active deformation of northern Borneo with small displacements relative to Sundaland and southern Borneo, suggesting broadly SW-directed movements up to 8 mm/yr. It is doubtful if they record anything other than movements of the upper crust. The orientation of GPS vectors is different from motions indicated by earthquake solutions and suggested by the orientation of structures offshore (e.g. Hazebroek and Tan, 1993; Hutchison, 2005; Hesse et al., 2009; Morley, 2009), and most GPS stations are close to the coast in areas likely to be underlain by weak sedimentary rocks or unconsolidated sediments; GPS vectors could simply reflect shallow displacements related to gravity-driven movements.

There are no active volcanoes in Sabah nor evidence for magmatism related to possible subduction at the troughs. In the Dent and Semporna peninsulas Mio-Pliocene volcanism was related to northward subduction of the Celebes Sea. Plio-Pleistocene volcanism in the Tawau area and Semporna peninsula (Kirk, 1968), and on small islands in Darvel Bay have an ocean-island basalt

character that reflects upwelling of melts in the upper mantle into lithospheric thin spots produced during earlier subduction (Macpherson et al., 2010).

The NW Borneo trough is a flexural response to gravity-driven deformation of the sediment wedge, caused by uplift on land that resulted from extension, with a contribution of deep crustal flow as explained by Hall (2013). For most of the offshore foldbelt extension and contraction can be balanced, consistent with a gravity-driven mechanism (Hesse et al., 2009). Further north, the Palawan Trough is the continent-ocean transition (Franke et al., 2011) at the SE edge of the modern South China Sea which formed in the Oligocene by rifting and is clearly unrelated to subduction.

## **CONCLUSIONS**

The term Proto-South China Sea was introduced to describe oceanic crust that formerly occupied the area south of Indochina and South China where the modern South China Sea is situated. The oceanic crust had a Mesozoic age, and has been completely eliminated by subduction beneath northern Borneo and Cagayan. Subduction began in the Eocene and ceased in the Early Miocene. The term Proto-South China Sea and the acronym (PSCS) should be used only for the slab subducted mainly beneath Sabah and Cagayan between the Eocene and Early Miocene. Oceanic crust subducted during earlier episodes of subduction in other areas should be named differently and we name lithosphere subducted under Borneo in the Cretaceous the Paleo-Pacific Ocean (PPO).

There is good evidence for subduction between the Eocene and Early Miocene in Sabah, and the western limit of Proto-South China Sea subduction was the West Baram Line. The subducted Proto-South China Sea can be imaged in the lower mantle using P-wave tomography. There was no subduction beneath Sarawak, SW of the West Baram Line, between the Eocene and Early Miocene where there was terrestrial to marginal marine deposition at this time.

The present-day NW Borneo Trough and Palawan Trough are not subduction trenches. The NW Borneo Trough is a flexural depression due to gravity-driven deformation of the Neogene sediment wedge west of Sabah, with a contribution of deep crustal flow. The Palawan Trough is the continent-ocean transition at the SE edge of the modern South China Sea.

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## FIGURE CAPTIONS

Figure 1. A. DEM of the South China Sea, Borneo, Palawan, Sulu Sea and Celebes Sea area with satellite gravity-derived bathymetry combined with SRTM topography (Sandwell and Smith, 2009). B. Principal features of the same area with bathymetry (Gebco, 2003).

Figure 2. The first reconstructions of the Proto-South China Sea. A: Holloway (1981, 1982); B: Taylor and Hayes (1983); C: Hinz et al. (1991). Taylor and Hayes did not name the Mesozoic oceanic crust but the reconstruction of Hinz et al. in which the term Proto-South China Sea was first used is almost identical to that of Taylor and Hayes except for the addition of the Borneo microcontinental plate in the SE.

Figure 3. Simplified geological map of Borneo based on Liechti et al. (1960), Lim and Heng (1985), Heng (1992), Douth (1992) and Tate (2001).

Figure 4. Simplified stratigraphy of northern Borneo based on Kirk (1957), Haile (1957), Liechti et al. (1960), Wolfenden (1960), Adams and Haak (1962), Haile (1962), Wilson and Wong (1964), Adams (1965), Collenette (1965), Tan (1979), BRGM (1982); Hutchison (1996, 2005, 2010a), Moss (1998), van Hattum et al. (2013), Thomson (2013) and Breitfeld (2015). The age of the Rajang Unconformity is uncertain and is in the range of c. 45 to c. 40 Ma.

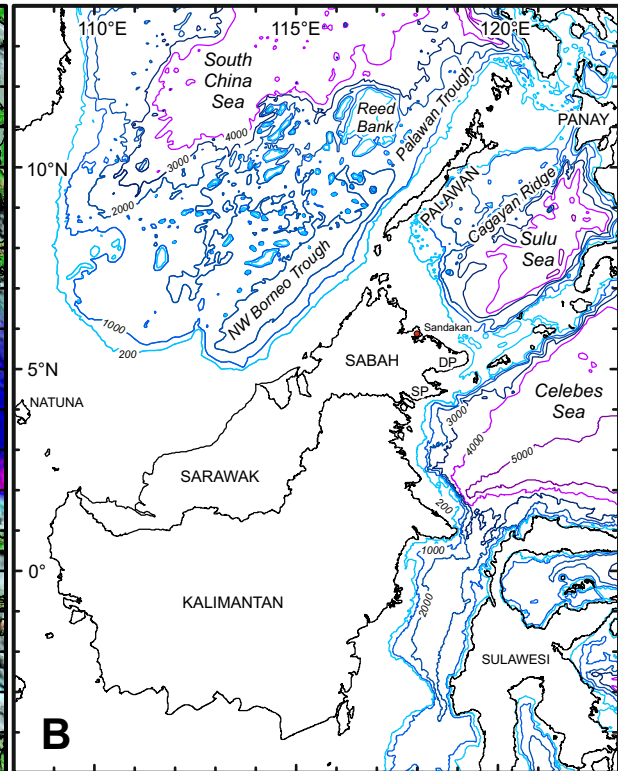
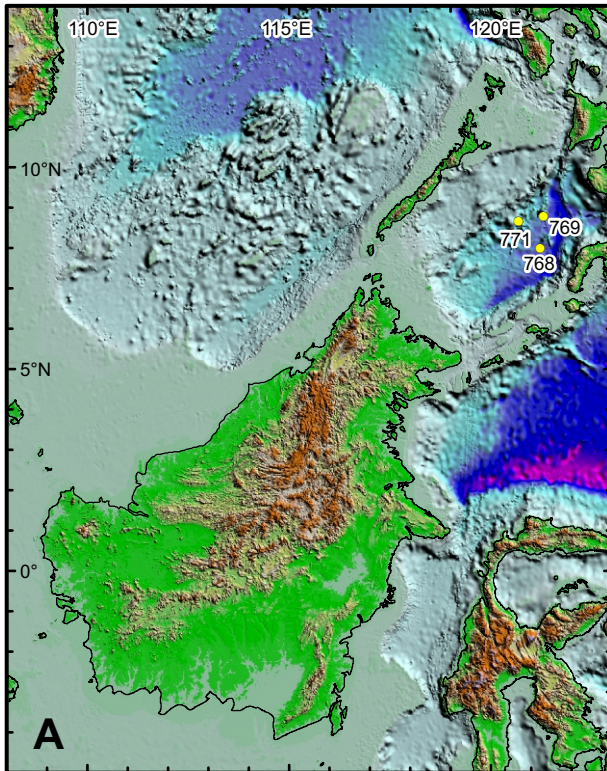
Figure 5. The structural zones of NW Borneo simplified after Haile (1974).

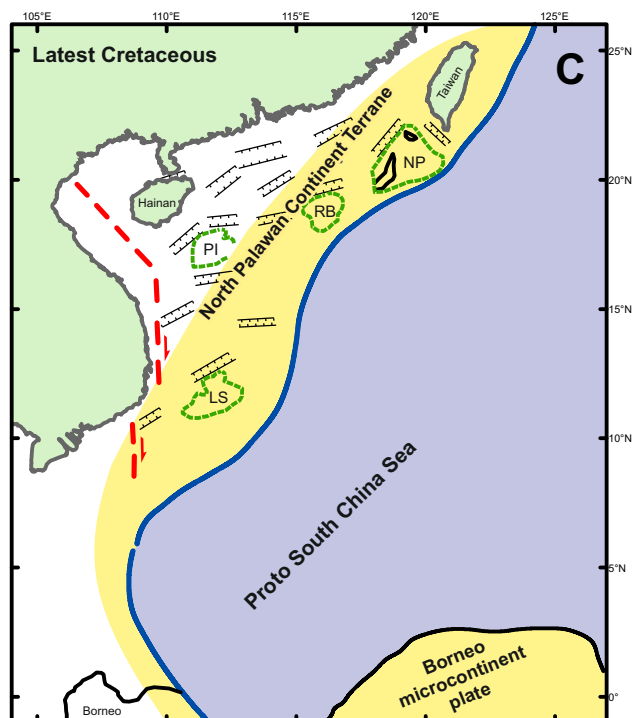
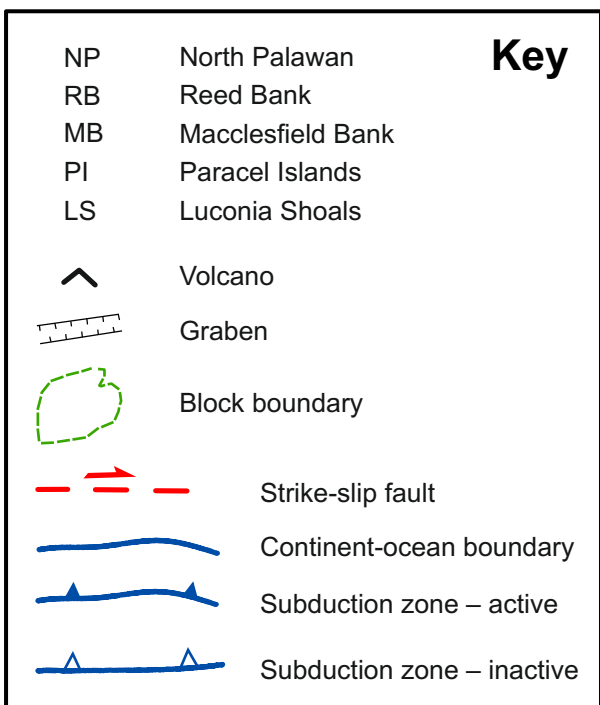
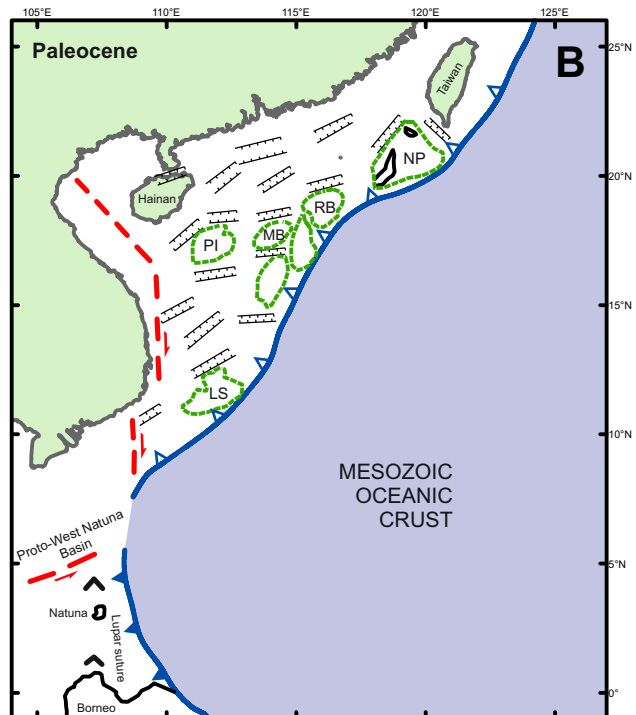
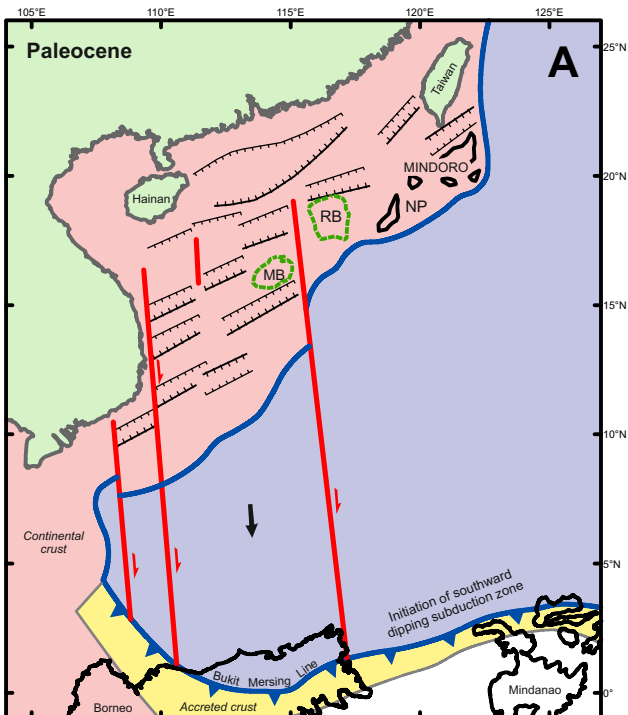
Figure 6. Schematic cross sections across Sarawak based on Moss (1998), redrawn and slightly modified from Hutchison (2010), who interpreted subduction at the Lupar Line and the Rajang Group (Sibu Zone) to have been deposited on Proto-South China Sea crust which had been subducted between 130 and 80 Ma.

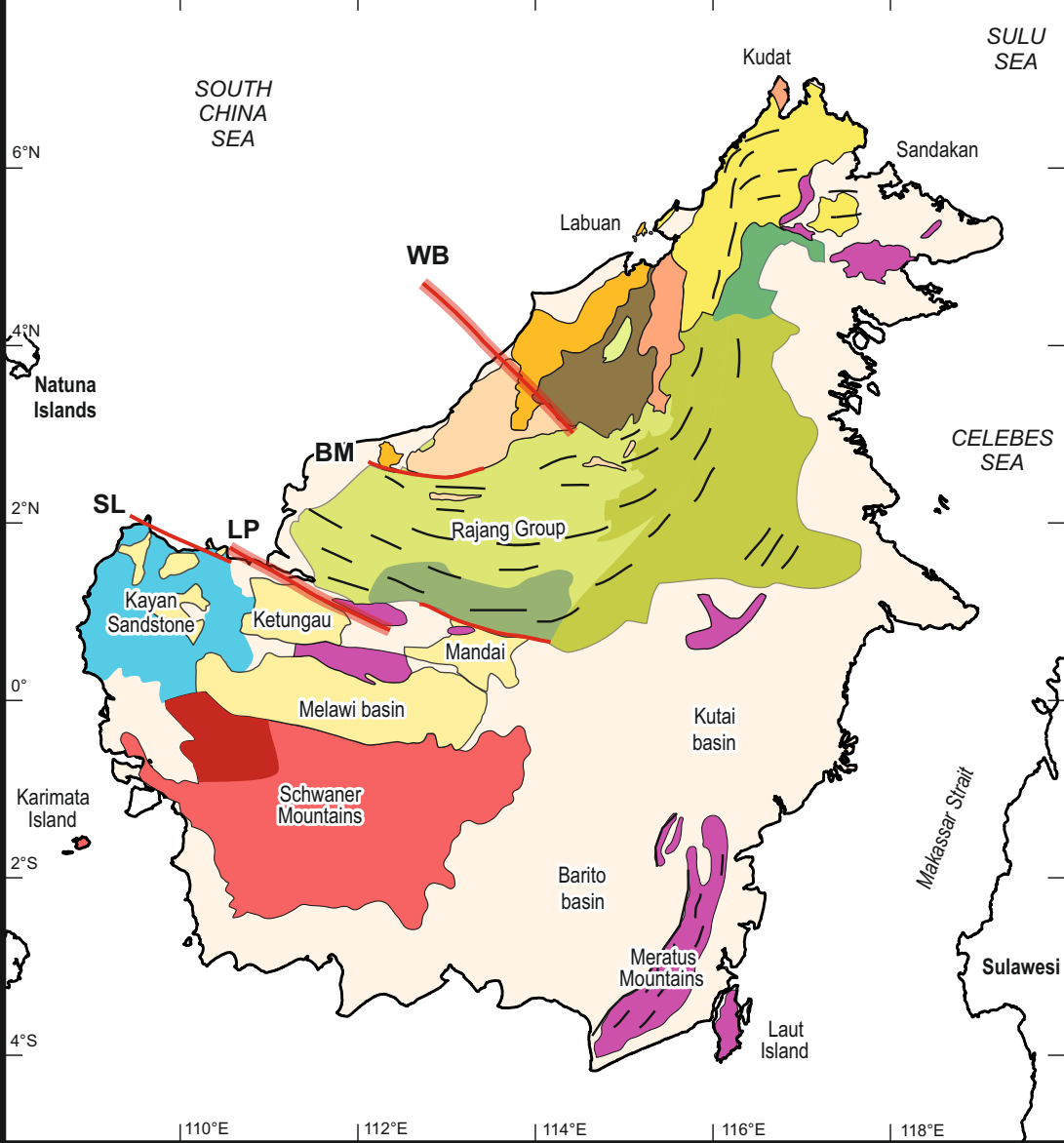
Figure 7. Paleogeography of the Borneo area in the mid Cretaceous as interpreted by Moss (1998) showing unsubducted Proto-South China Sea north of Sabah and trapped oceanic crust of the Proto-South China Sea on which Embaluh–Rajang Group sediments were later deposited.

Figure 8. A. Lower mantle tomographic depth slice at 800 km from Hall and Spakman (2015) showing high velocity anomalies. Anomalies east of about 110°E are interpreted as the result of subduction since 45 Ma. The anomaly due to the subducted Proto-South China Sea is labelled. B. Reconstruction at 30 Ma modified from Hall (2012) showing interpreted subduction zones. Sunda-Java trench subduction, Proto-South China Sea subduction, subduction below North Sulawesi-East Philippines,

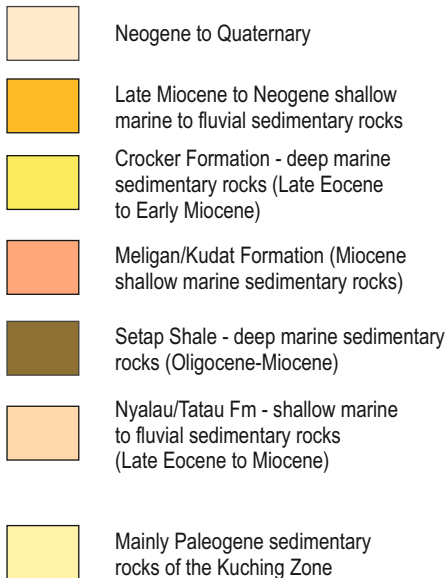
and subduction below NE side of Philippine Sea plate all fit well with position of high velocity anomalies in lower mantle. The area shaded brown in Sabah represents the Crocker and related formations on land.



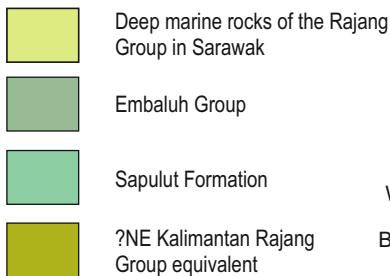




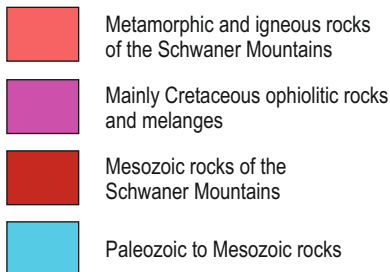
### Cenozoic



### Rajang Group (Late Cretaceous to Eocene)



### Pre-Cretaceous



Major lineament



Major faults



SL Serabang Line

LP Lupar Line

WB West Baram Line

BM Bukit Mersing Line



Era	Epoch	Age Ma	SW	Kuching Zone	Sibu and Miri Zones	Sabah, Brunei and Labuan	NE
Neogene	Pleistocene	2.6					<b>Unconformity</b>
	Pliocene	5.3					<b>DRU</b> Deep Regional Unconformity
	Miocene	23.0					<b>TCU</b> Top Crocker Unconformity
Paleogene	Oligocene	33.9	<b>Mel/Kud</b> Meligan + Kudat Formation				<b>Crocker Formation equivalents</b>
	Eocene	~45					<b>Gom</b> Gomantong Limestone
		56.0					<b>Lab</b> Labang Formation
Cretaceous	Paleocene	66.0	<b>Kul</b> Kulapis Formation				<b>Tem</b> Temburong Formation
	Late Cretaceous	80.0					<b>Tru</b> Trusmadi Formation
							<b>Melinau</b> Melinau Limestone Formation
							<b>?Rajang Group equivalent in NE Kalimantan</b>
							<b>Lurah Formation</b>
							<b>Longbawan Formation</b>
							<b>Mentarang Formation</b>

